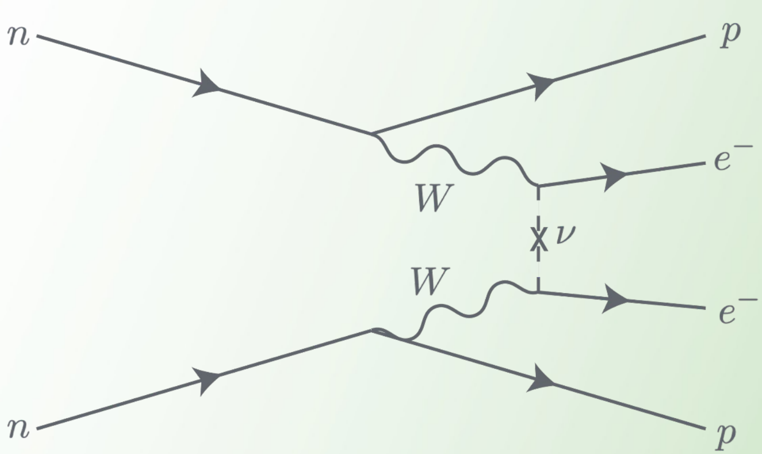
Overview of Neutrinoless Double Beta Decay

Krishan Mistry



CONFERENCE ON SCIENCE AT THE SANFORD UNDERGROUND RESEARCH FACILITY

South Dakota Mines campus, May 14-16, 2024

UTA

ADT UTA Center for Advanced Detector Technologies

νRES NEUTRINOS AND RARE EVENT SEARCHES

May 15 2024

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How did the Universe come to be?

- Standard Model is our best theory but it has some shortfalls
- Neutrinos are one of the least understood particles in the SM and may give some clues

Neutrino mass mechanism

Antimatter-matter asymmetry

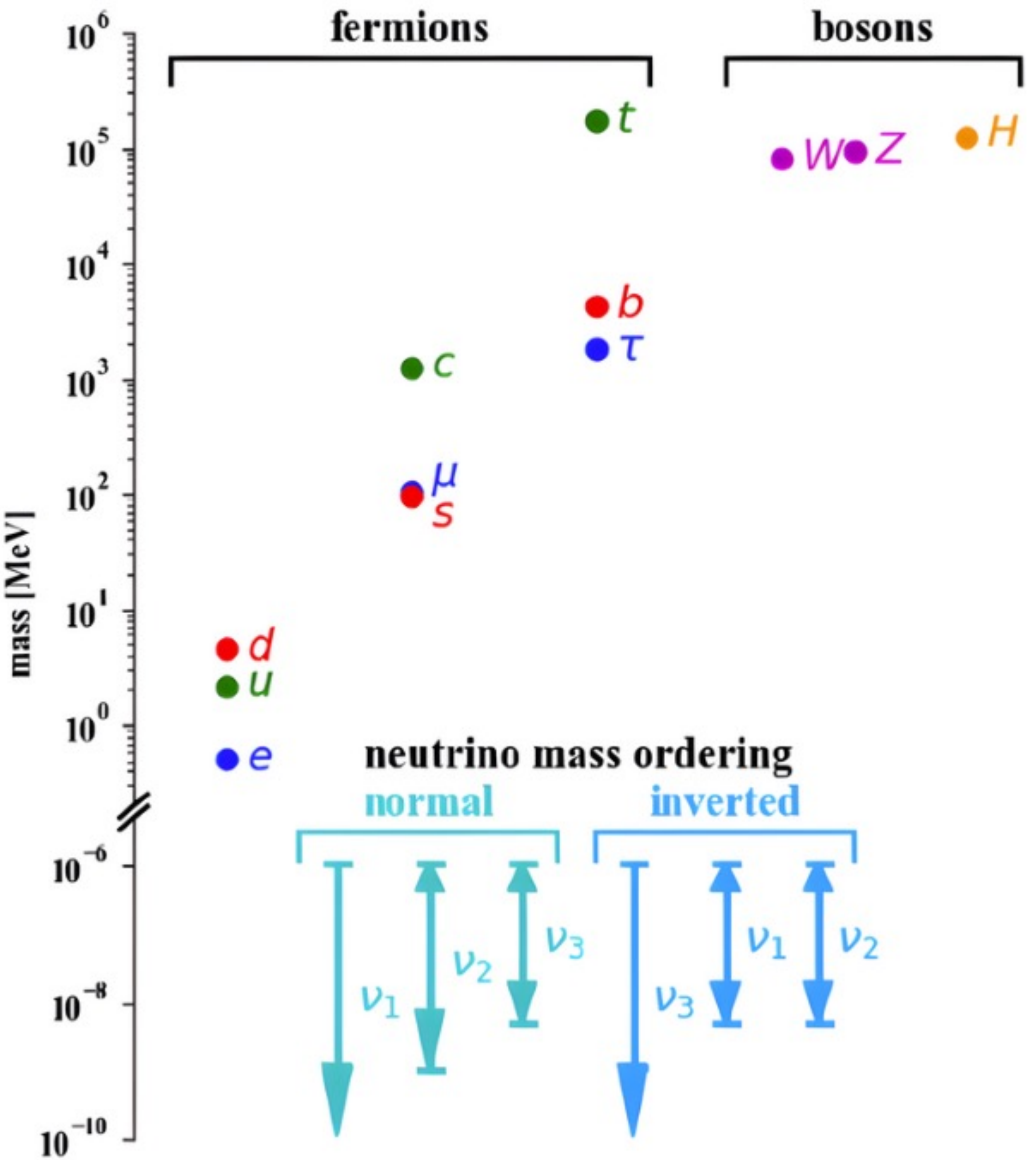
Dark Matter/Energy

Grand Unified Theory

Quantum Gravity

ν's have mass and it's really small!

- Standard Model includes massless neutrinos
- Discovery of neutrino oscillations means they have mass
  - Significantly smaller scale to the regular fermions
- Fine-tuning of the SM, new mass mechanism, new physics?



Adding a mass term

- If we include mass mechanism like the other fermions, we add a right-handed (but sterile) neutrino:

Yukawa coupling

$$-L_D = m_D(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L), \qquad m_D = y\, v/\sqrt{2}$$

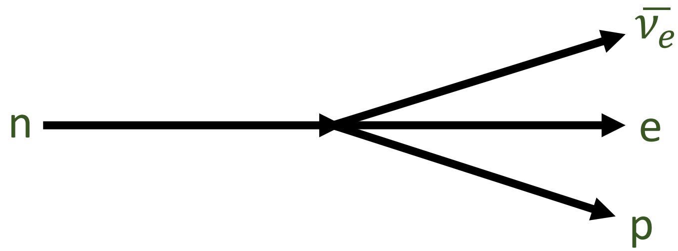
Expectation value of Higgs after EW symmetry breaking

- Yukawa coupling constant has to be extremely small (~10^{-12})
    - Fine-tuning and seems unnatural

- Doesn't get us any closer to solving any of the big questions

Rewind History: Fermi Beta Decay

- Fermi's theory of beta decay (1930s) was first developed assuming a point-like interaction between fermions



- We later found out that the mediator bosons were at much higher energy scale than the MeV scale energies probed
- Fermi's description was just a low-energy manifestation of the Standard Model
- Electroweak interactions at a higher physics scale

SM is a low-energy effective field theory (EFT)

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \cdots$$

The only dimention-5 operator we can add obeying SM gauge symmetry

$$\frac{L_1}{E_{new}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{new}}$$

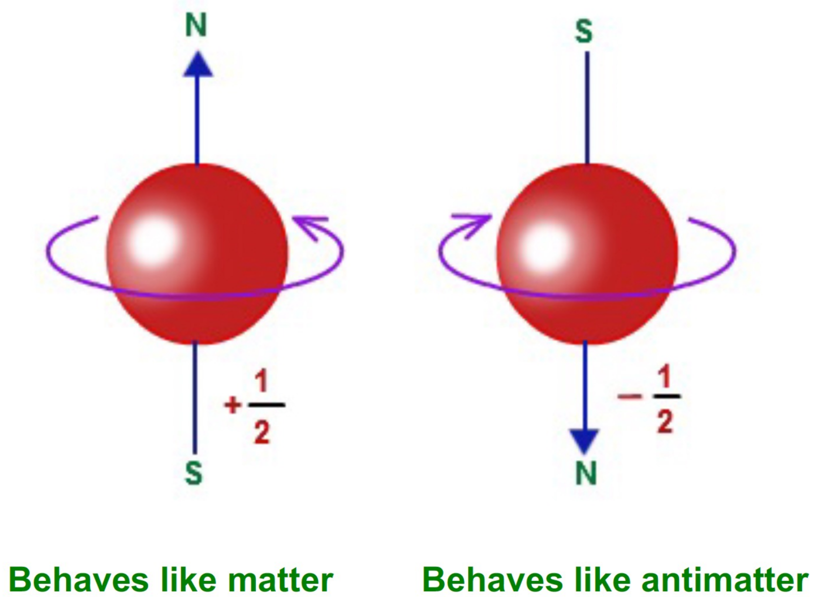
Weinberg 1979

- Term has one function: makes Majorana neutrinos with mass suppressed by new physics scale E_{new}

- Also makes the theory non-renormalizable implying there must be something else at high scale too

The Majorana Neutrino

- Ettore Majorana realized for neutral fermions you can impose the condition: $\nu^C = \nu$
  - Neutrino is the only fermion that you can impose this condition



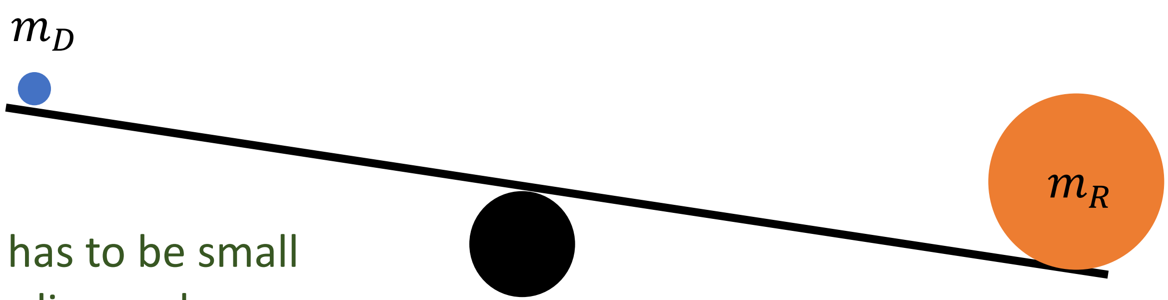
- A Majorana neutrino introduces processes that violates lepton number by two units

Majorana mass generation mechanism (Seesaw Type I)

$$-L_{D+R} = m_D(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L) + \frac{1}{2}m_R(\overline{\nu_R}(\nu_R)^C + \overline{(\nu_R)^C}\nu_R)$$

Dirac Mass term

Right-handed Majorana term



m_D no longer has to be small
→ Yukawa coupling no longer has to be unnaturally small

m_R >> m_D as no longer fixed to EW scale

- Definite mass states of Dirac + right-handed Majorana mass results in a left-handed Majorana neutrino of mass m_D^2/m_R
  - → We have a more natural way to explain the neutrino mass
- Integration of the heavy field out below the mass scale m_R returns the Weinberg operator

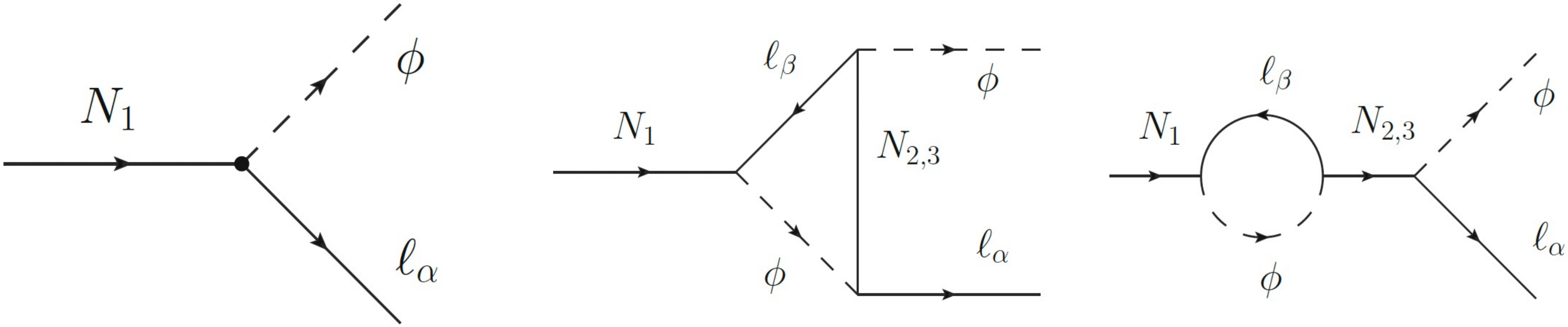
Leptogenesis

Fukugita and Yanagida, Phys, Lett., B174:45,1986

- Introduce a heavy Majorana neutrino (typically around GUT scale)
  - Decays to leptons+Higgs: $l_\alpha \phi$ and $\overline{l_\alpha} \bar{\phi}$
  - If rate of interaction is slower than universe expansion, we depart from thermal equilibrium
  - We can drive one decay process more than the other creating LNV

- Sphaleron process then generates the baryon asymmetry from LNV

- Sakharov conditions to explain antimatter-matter asymmetry: BNV, BSM CPV, thermal equilibrium



In a nutshell, Majorana neutrinos:

1. Violate lepton number conservation

2. Neither matter or antimatter, but something else (Majorana fermion)

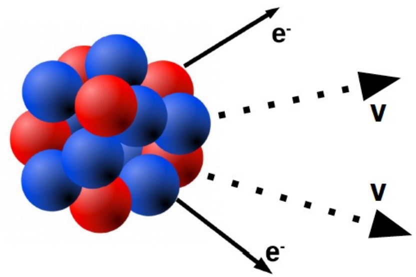
3. The SM with a Majorana term is non-renormalizable
   - → SM is definitely a low-energy effective field theory

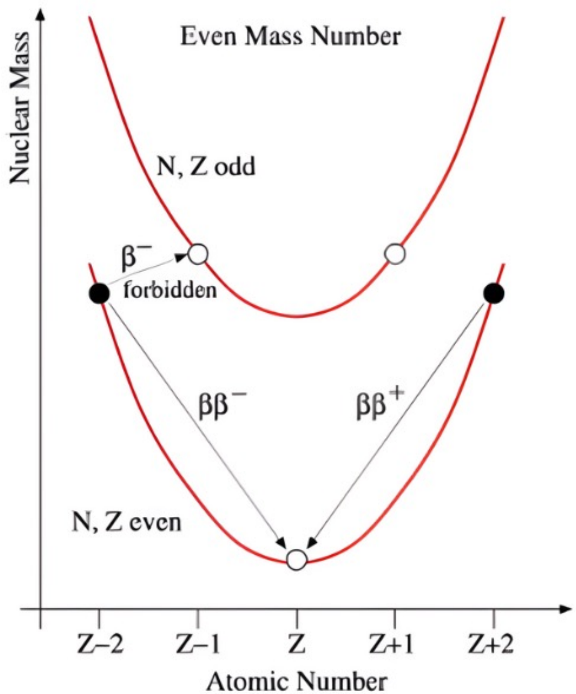
4. There are other mass generation mechanisms beyond the Higgs

5. Majorana neutrinos are a prediction of Leptogenesis to explain the antimatter-matter asymmetry

Double Beta decay $(2\nu\beta\beta)$

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\nu}_e$$



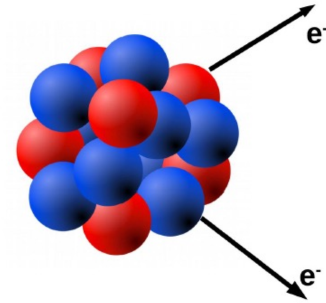


- A known (and measured) SM process
- Even-even nuclei are more stable due to the pairing-force
- Transition is mostly to ground state
  - Excited states are suppressed by phase-space
- Second order weak process
  - Half-lives ~10^{19}-10^{21} yr

Neutrinoless Double Beta decay $(0\nu\beta\beta)$

- Majorana neutrinos annihilate giving almost all the energy to the electrons
  - Cannot happen for Dirac neutrino

$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$



$$T_{1/2} = \left[\, G \times |M(g_A)|^2 \times m_{\beta\beta}^2 / \mathrm{m}_{\mathrm{e}}^2 \right]^{-1}$$

Phase-space factor
Atomic Physics

Matrix element
Nuclear Physics

Effective mass of neutrino
Particle Physics

Your choice of double-beta decay isotope

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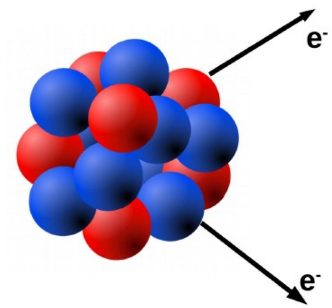
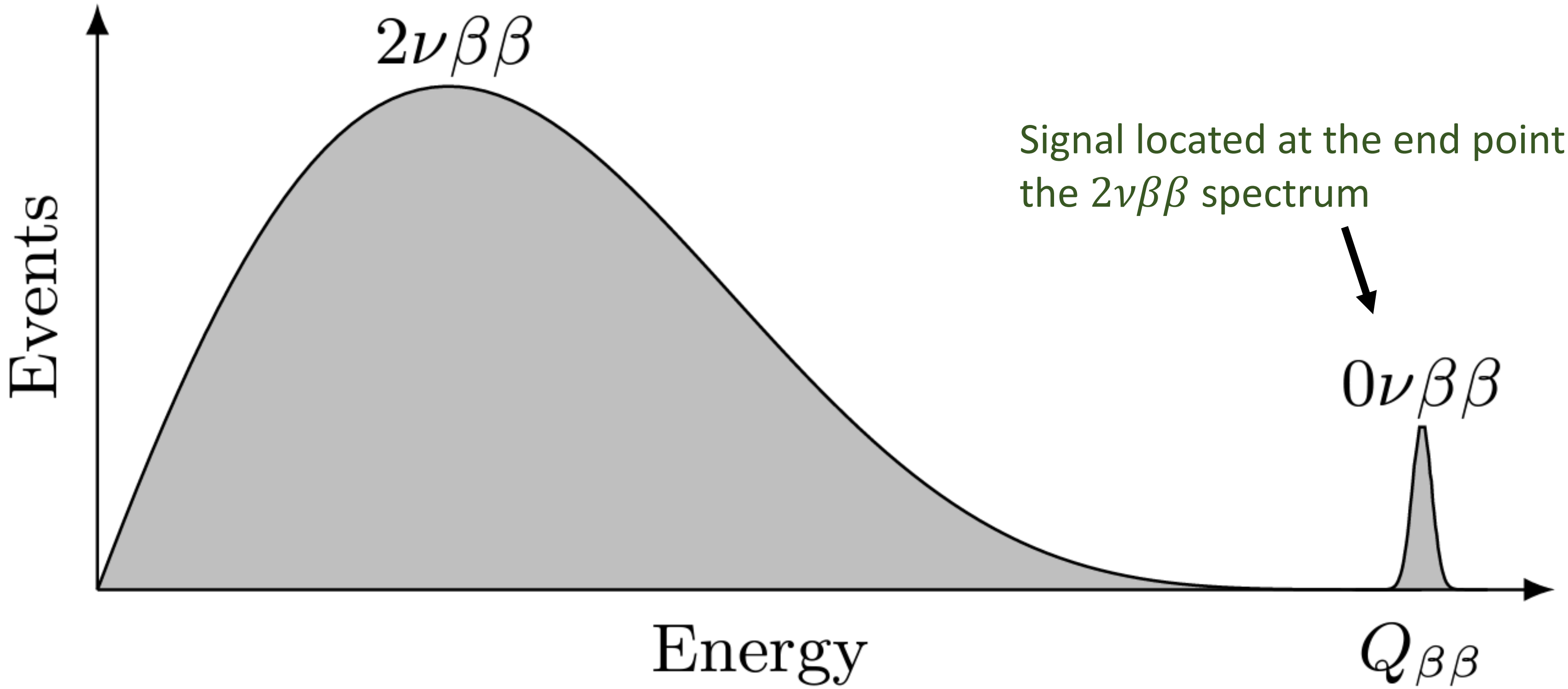
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

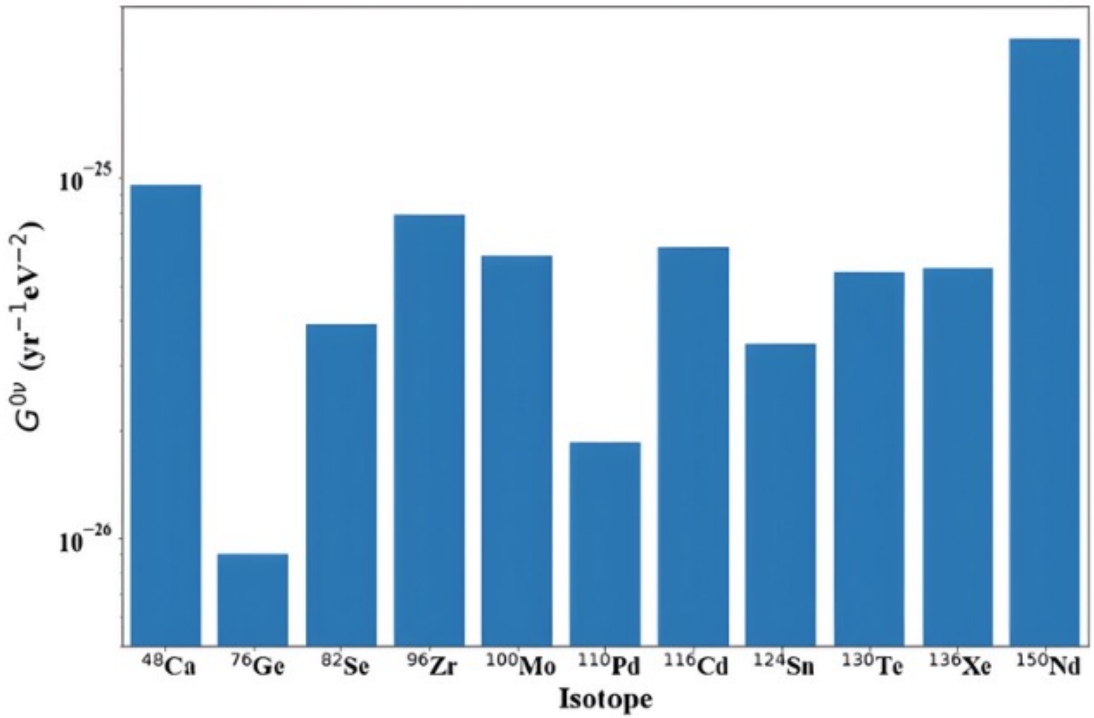




Signal located at the end point of the $2\nu\beta\beta$ spectrum

Phase Space Factor: G

- Factor accounts for the atomic physics relating to the emitted electrons
- Depends on the Q^5 and Z of the isotope
- Can be calculated with reasonable accuracy
  - Need good accurate description of the Coulomb field on the decay electron wave-functions



Nuclear Matrix Elements (NME): $|M^2|$

- Accounts for the structure of the initial and final states of the nucleus
  - Challenging and is one of the largest sources of theoretical uncertainty

$$M = M_{\text{long}} + M_{\text{short}}$$

$$g_A^2 M_{GT} - g_V^2 M_F + g_A^2 M_T$$

Gamow-Teller Fermi Tensor

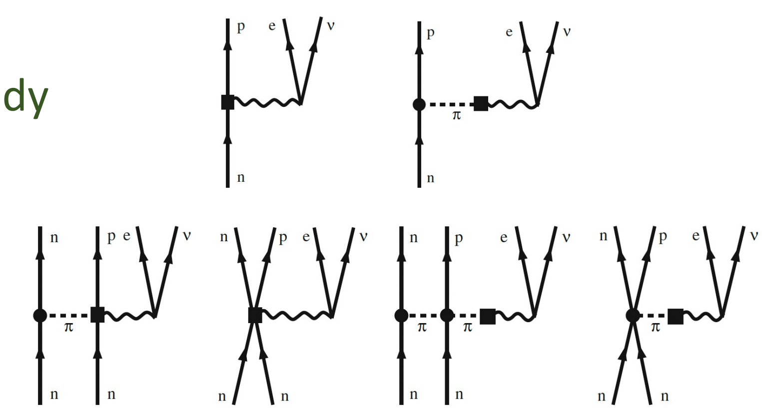
$$2 g_\nu^{NN} m_\pi^2 M_{CT}$$

Contact Operator

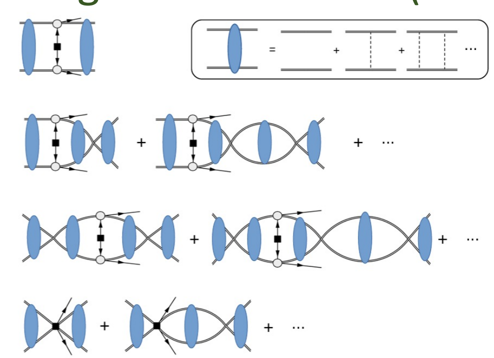
Weak nucleon currents

1-body

2-body



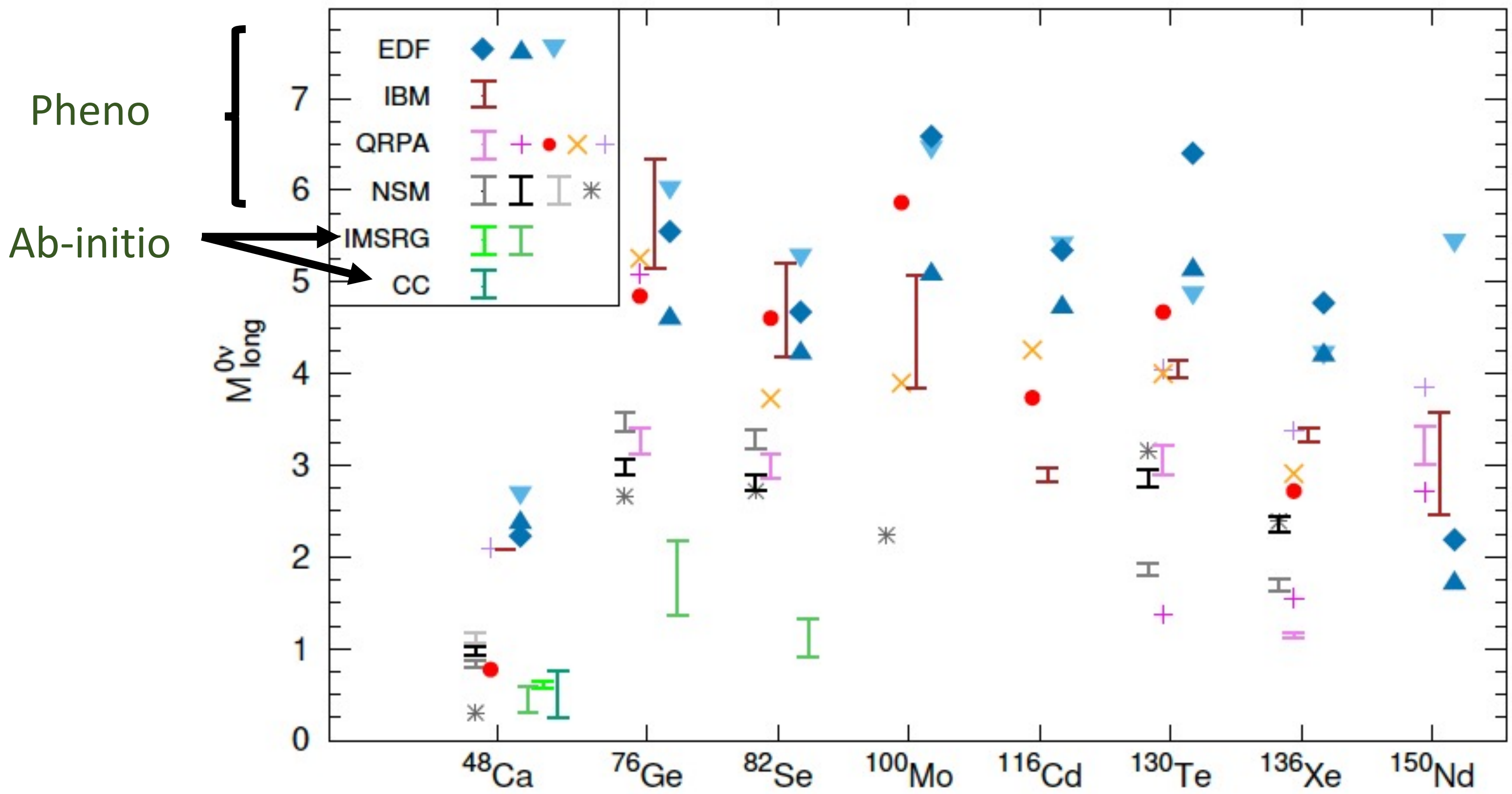
New term added to account for short-range contributions (2018)



Cirigliano, et al, Phys. Rev. Lett. 120, 202001

Nuclear Matrix Elements (NME): $|M^2|$

- Phenomenological nuclear models have variability, each with different physics approaches
  - ⇥ Lack of constraining data
  - ⇥ Spread is dependent on isotope



Nuclear Matrix Elements (NME): $|M^2|$

- Phenomenological nuclear models have variability, each with different physics approaches
  - Lack of constraining data
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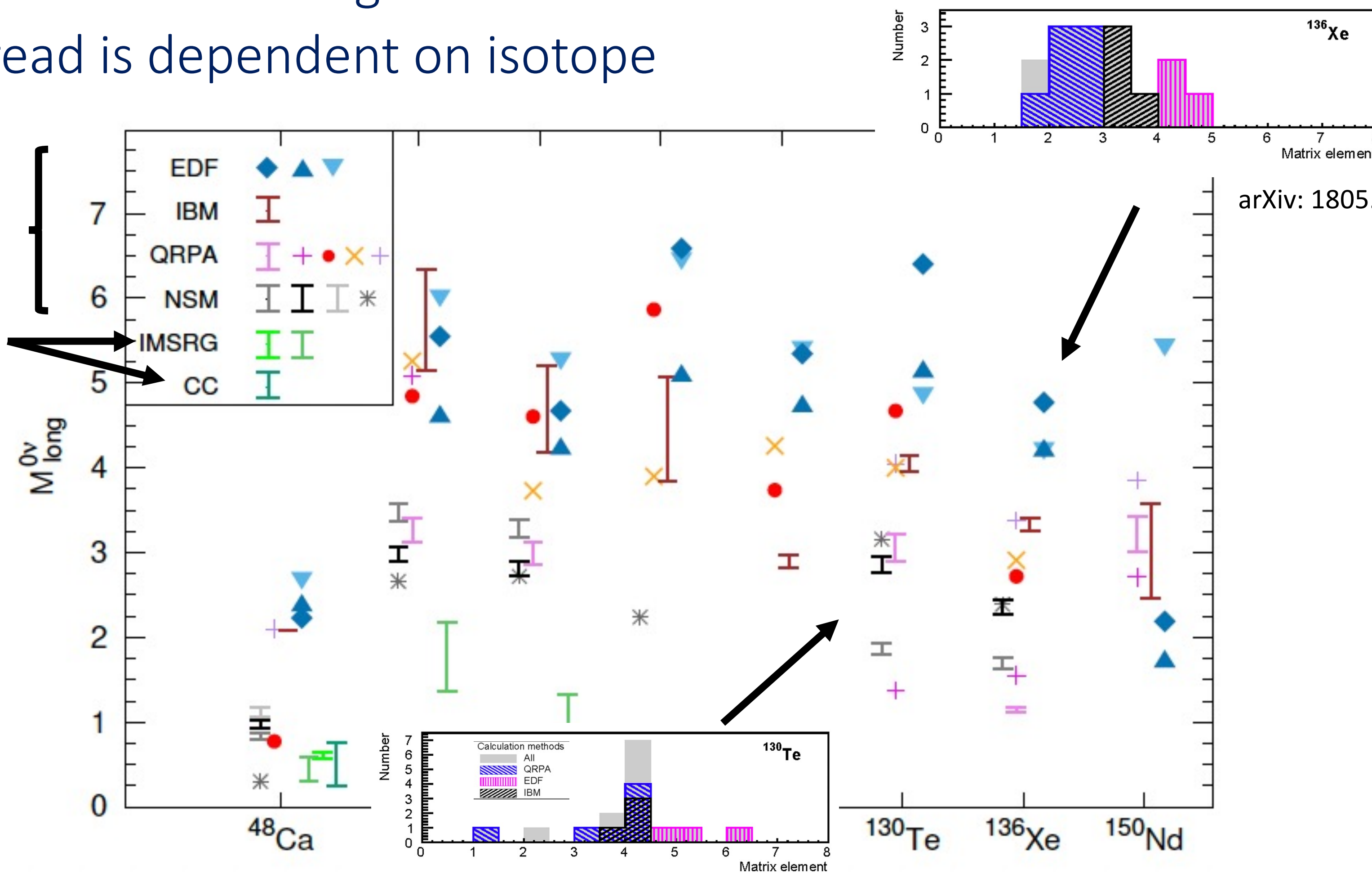
Some clustering of pheno predictions towards a central value

Pheno

Ab-initio



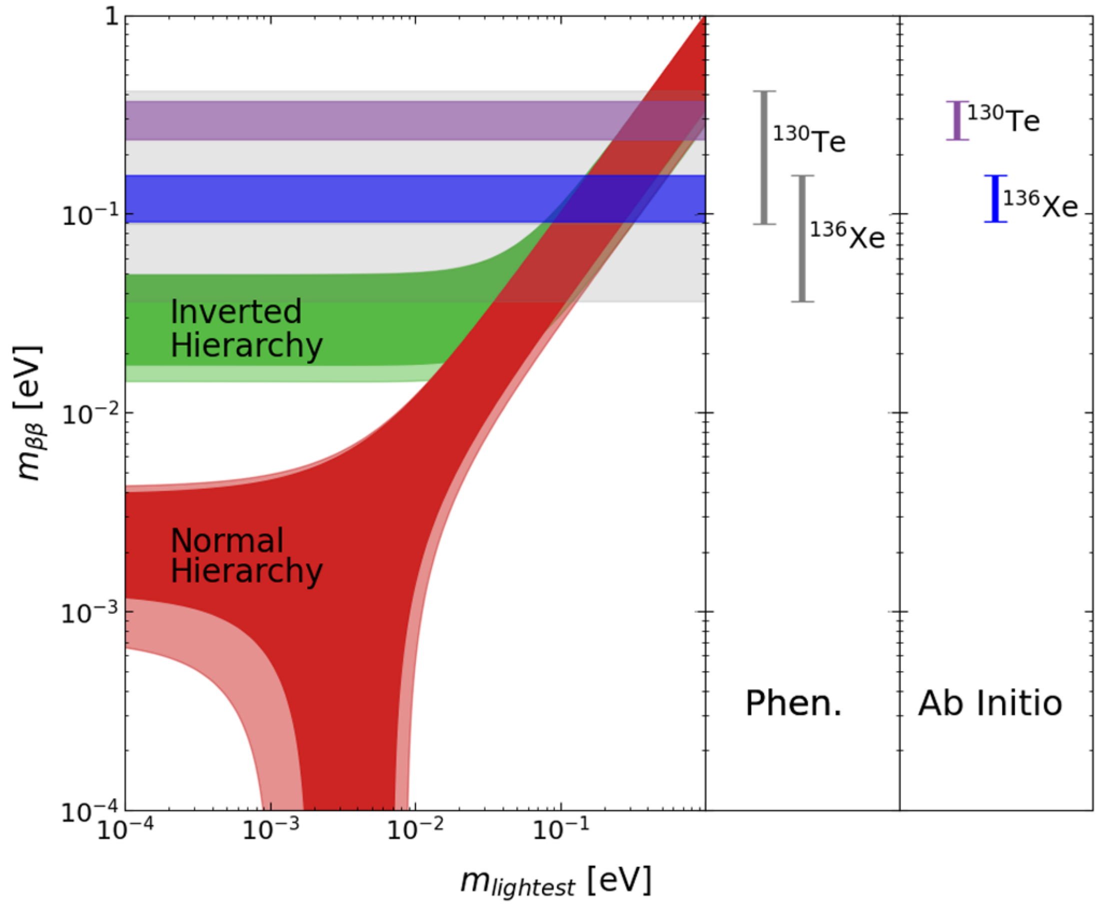
arXiv: 1805.11142

Recent Ab-initio Calculations

- Recent Ab-initio calculations tend to reduce the NME with reduced uncertainty
  - Better control of g_A quenching and short-range contributions

- Refinements are still being made to the calculations e.g. higher order terms (IMSRG(3))

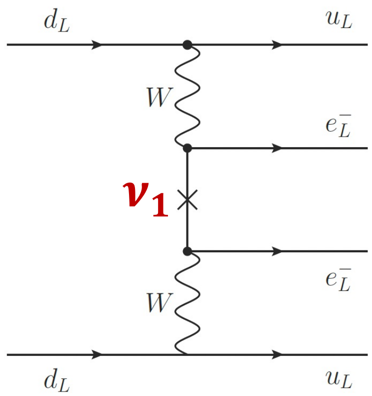
- Inverted hierarchy in non-degenerate region may not have been probed yet with current ab-initio estimates

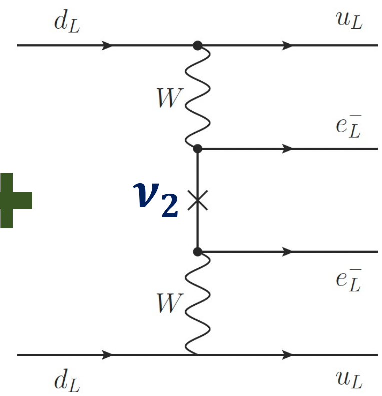


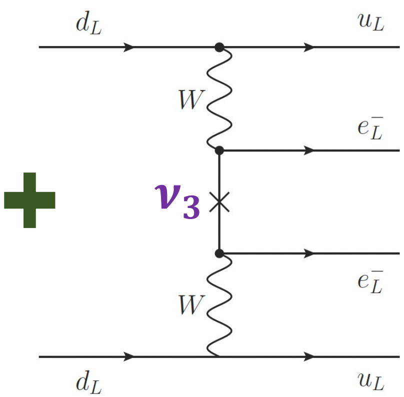
Belley et al, arXiv 2307.15156 (2023)

$m_{\beta\beta}$ in the minimal mechanism

Minimal mechanism: exchange of light Majorana neutrinos

$m_{\beta\beta} = \Big|$ 

$+$ 

$+$ 

$\Big|^2$

$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

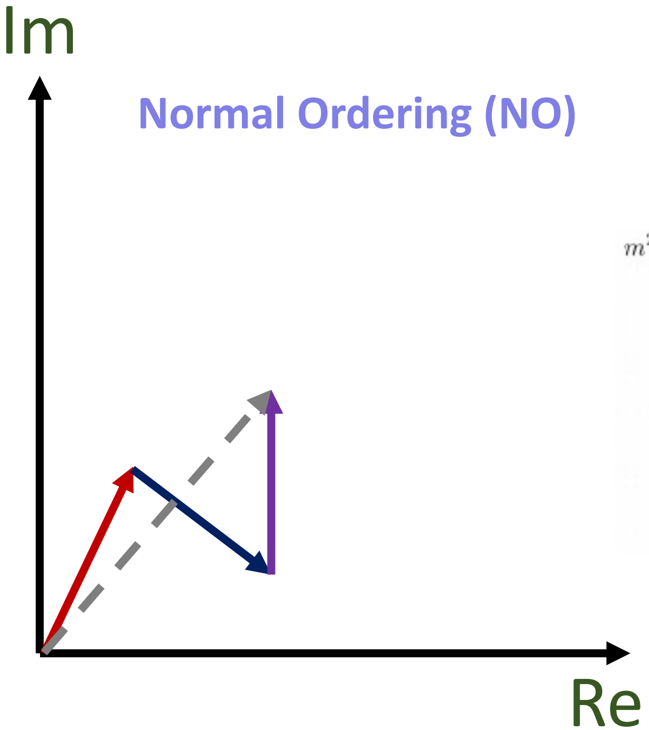
$$= \left| c_{12}^2 c_{13}^2 e^{2i\alpha} m_1 + c_{12}^2 s_{12}^2 e^{2i\beta} m_2 + s_{13}^2 m_3 \right|^2$$

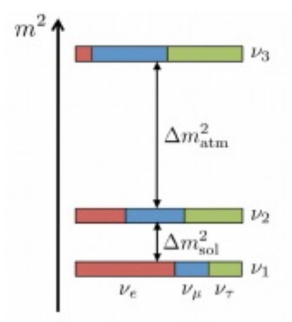
$m_{\beta\beta}$ in the minimal mechanism

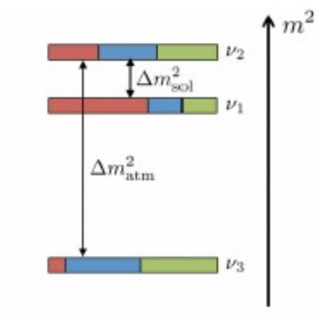
Minimal mechanism: exchange of light Majorana neutrinos

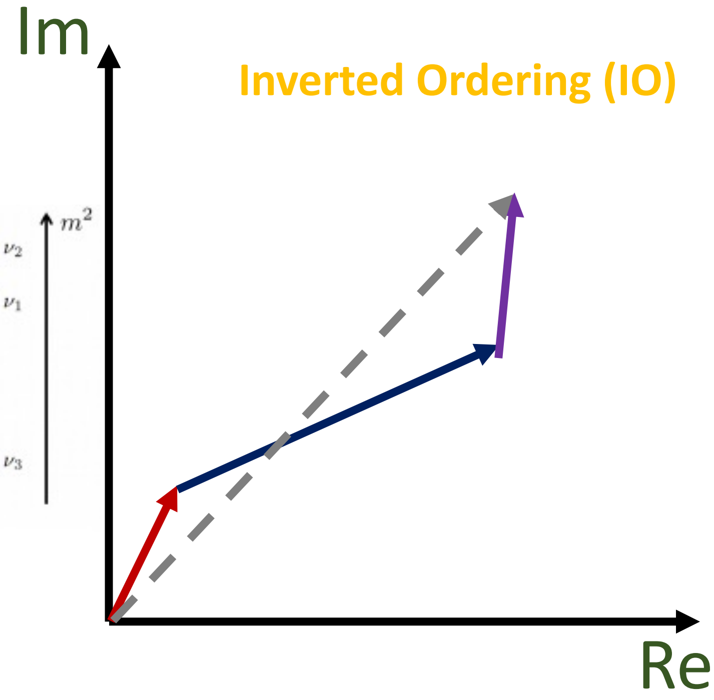
$$m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 e^{2i\alpha} m_1 + c_{12}^2 s_{12}^2 e^{2i\beta} m_2 + s_{13}^2 m_3 \right|^2$$

α and β are unknown CP phases not determinable by neutrino oscillations



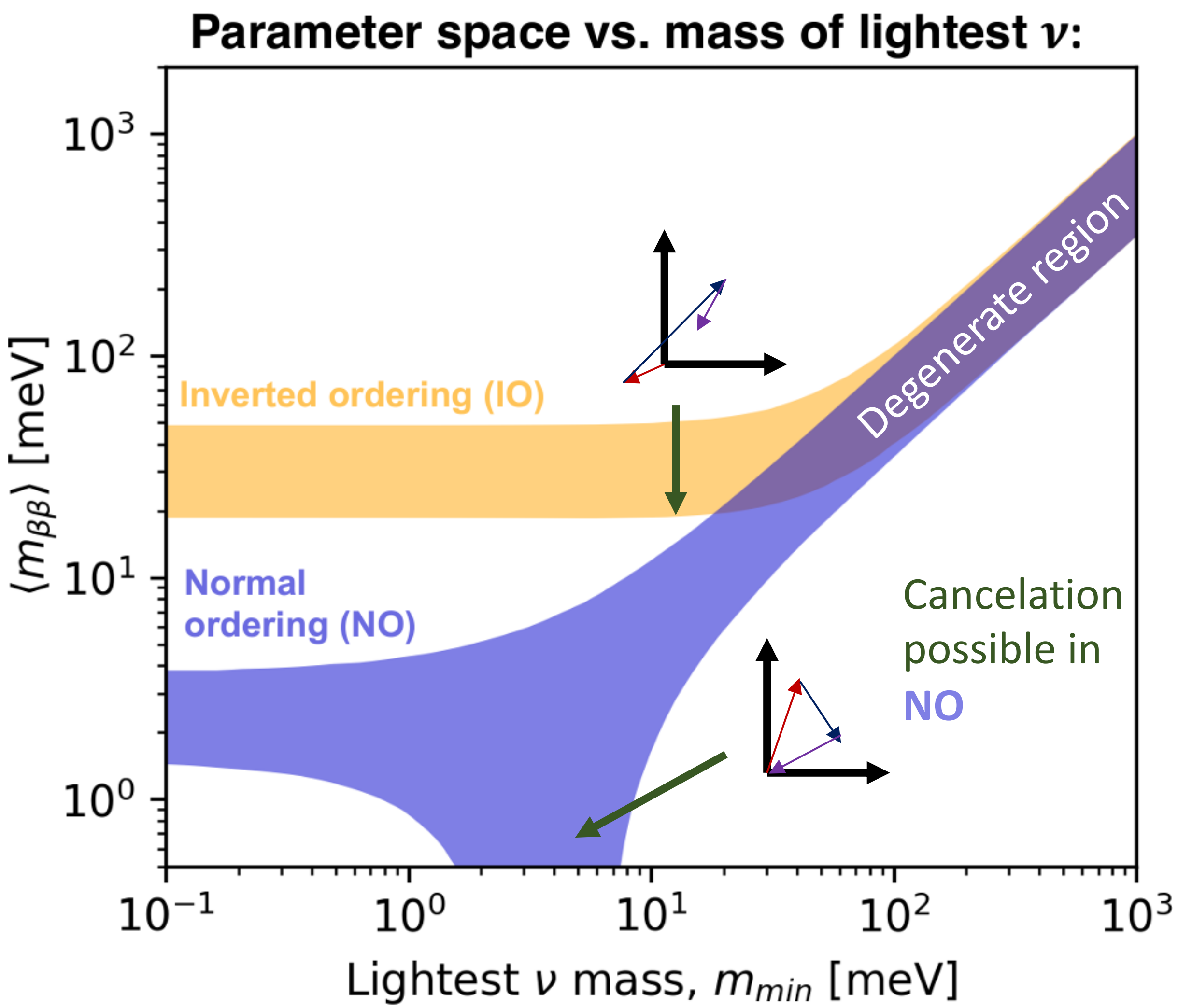






$m_{\beta\beta}$ in the minimal mechanism

- NO and IO have different lightest neutrino mass
- Thickness to bands due to uncertainty on phases
- Smallest value of $m_{\beta\beta}$ in IO is ~20meV

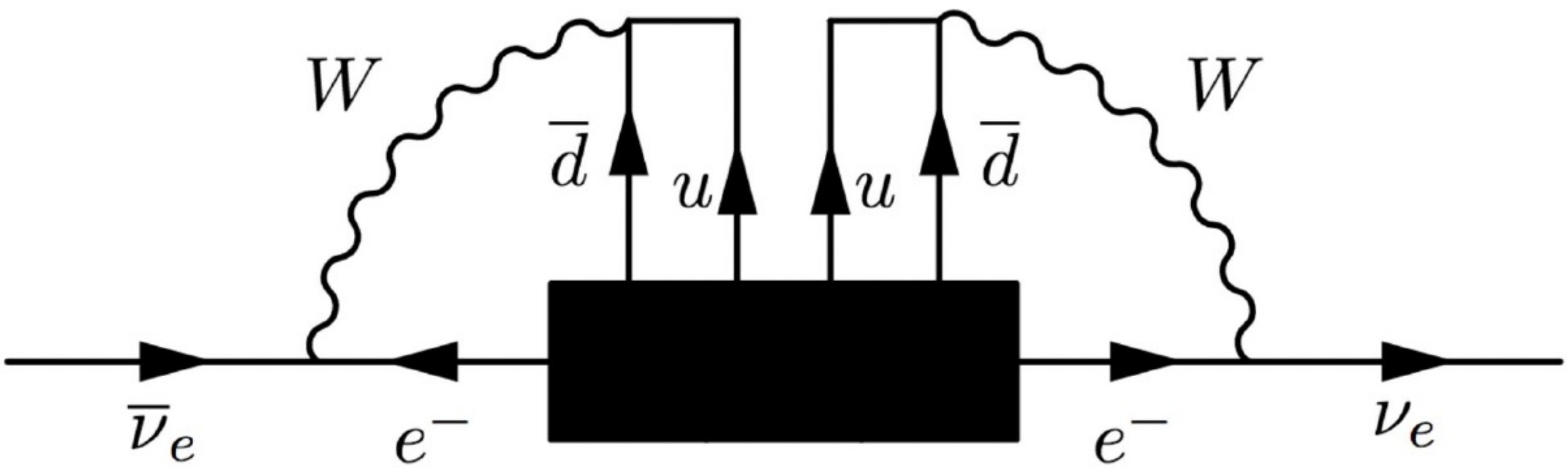


Black Box Theorem (Schechter-Valle)

J. Schechter and J. W. F. Valle
Phys. Rev. D 25, 2951

- Light Majorana exchange may induce $0\nu\beta\beta$ and a give source of LNV
  - It may not be the only mechanism driving the process

- Black-box theorem states that for any possible source of LNV that causes $0\nu\beta\beta$, we can draw a Feynman diagram enclosing this new physics
  - We still learn neutrinos are Majorana from observing $0\nu\beta\beta$

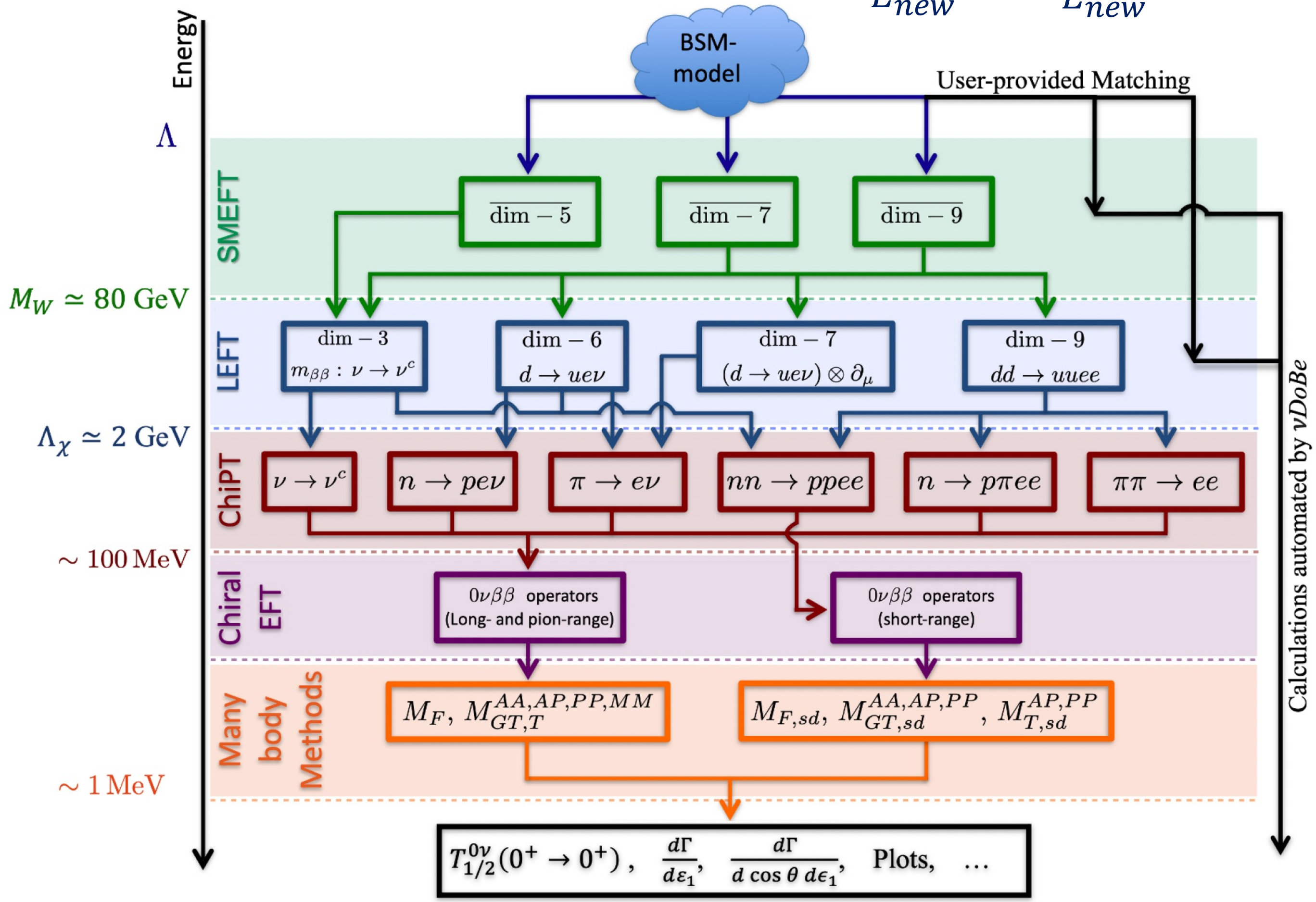


Decay Rate with higher dim operators

- More general form of the decay rate accounting for LNV physics in an EFT framework

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \cdots$$

- Odd operators provide sources of LNV
- Higher order operators can also drive the rate of $0\nu\beta\beta$!



Scholer, O., de Vries, J. & Gráf, L. *J. High Energ. Phys.* **2023**, 43 (2023).

Decay Rate with higher dim operators

- More general form of the decay rate accounting for LNV physics in an EFT framework: “Master Formula”

$$T_{1/2} = \left[g_A^4 \sum_k G_{0k} |\mathcal{A}_k(\{C_i\})|^2 \right]^{-1}$$

Phase-space factor

Sub-amplitudes that depend on:

- NME
- low-energy constants e.g. g_ν^{NN}
- Wilson Coefficients (C_i)

Class	Op. Name	Code Label	Op. Structure	Half-Life Group	SMEFT Dim.
			Dim 3		
Ψ^2	$\mathcal{O}_{m_{\beta\beta}}$	m_bb	$-\frac{1}{2} m_{ee} \overline{\nu_{L,e}^C} \nu_{L,e}$	$m_{\beta\beta}$	5
			Dim 6		
Ψ^4	$\mathcal{O}_{SL}^{(6)}$	SL(6)	$[\overline{u_R} d_L][\overline{e_L} \nu_L^C]$	$C_S^{(6)}$	7
	$\mathcal{O}_{SR}^{(6)}$	SR(6)	$[\overline{u_L} d_R][\overline{e_L} \nu_L^C]$	$C_S^{(6)}$	7
	$\mathcal{O}_{VL}^{(6)}$	VL(6)	$[\overline{u_L} \gamma^\mu d_L][\overline{e_R} \gamma_\mu \nu_L^C]$	$C_{VL}^{(6)}$	7
	$\mathcal{O}_{VR}^{(6)}$	VR(6)	$[\overline{u_R} \gamma^\mu d_R][\overline{e_R} \gamma_\mu \nu_L^C]$	$C_{VR}^{(6)}$	7
	$\mathcal{O}_{T}^{(6)}$	T(6)	$[\overline{u_L} \sigma^{\mu\nu} d_R][\overline{e_L} \sigma_{\mu\nu} \nu_L^C]$	$C_T^{(6)}$	7
			Dim 7		
$\Psi^4\partial$	VL(7)	$\mathcal{O}_{VL}^{(7)}$	$[\overline{u_L} \gamma^\mu d_L][\overline{e_L} \overleftrightarrow{\partial}_\mu \nu_L^C]$	$C_V^{(7)}$	7
	$\mathcal{O}_{VR}^{(7)}$	VR(7)	$[\overline{u_R} \gamma^\mu d_R][\overline{e_L} \overleftrightarrow{\partial}_\mu \nu_L^C]$	$C_V^{(7)}$	7

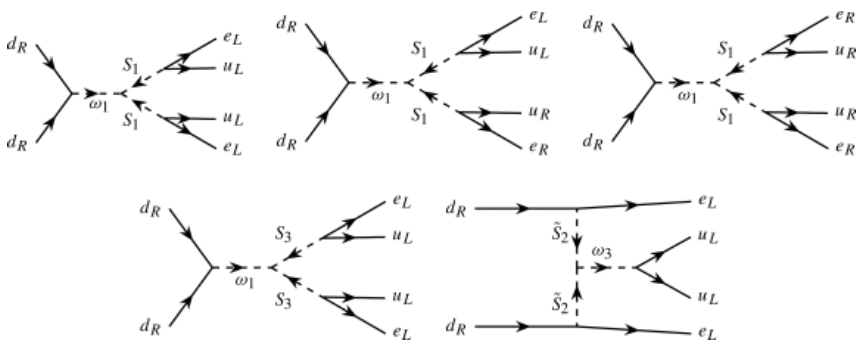
Testing EFT Models

- Electron energy and angular kinematics can be different for your model

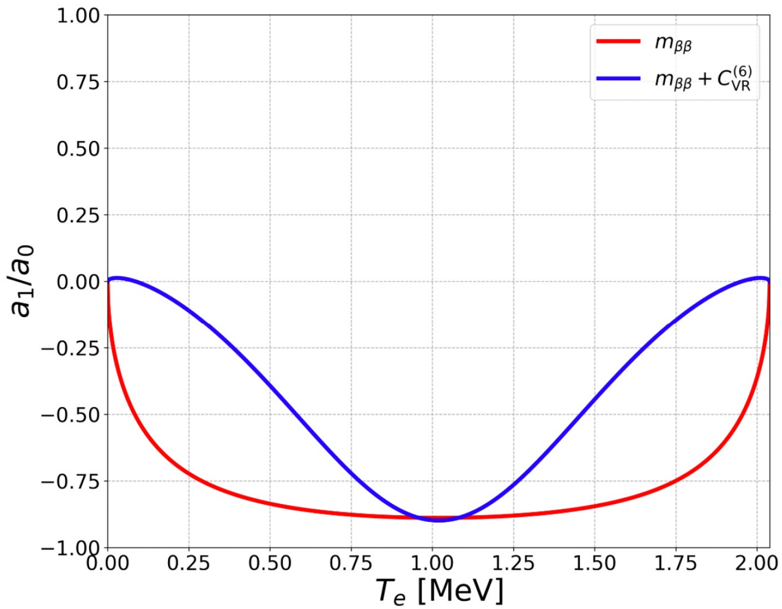
- If your detector can resolve the electron tracks, you can tell the difference!

Figure made with νDoBE → generator to calculate your EFT event spectra!

Your favourite LNV theory



Leptoquarks, SUSY, Kaluza Klein, LR symmetric couplings, etc



[Scholer, O., de Vries, J. & Gráf, L. *J. High Energ. Phys.* **2023**, 43 (2023).]

Testing EFT Models

- Electron energy and angular kinematics can be different for your model

- If your detector can resolve the electron tracks, you can tell the difference! e.g. NEXT!

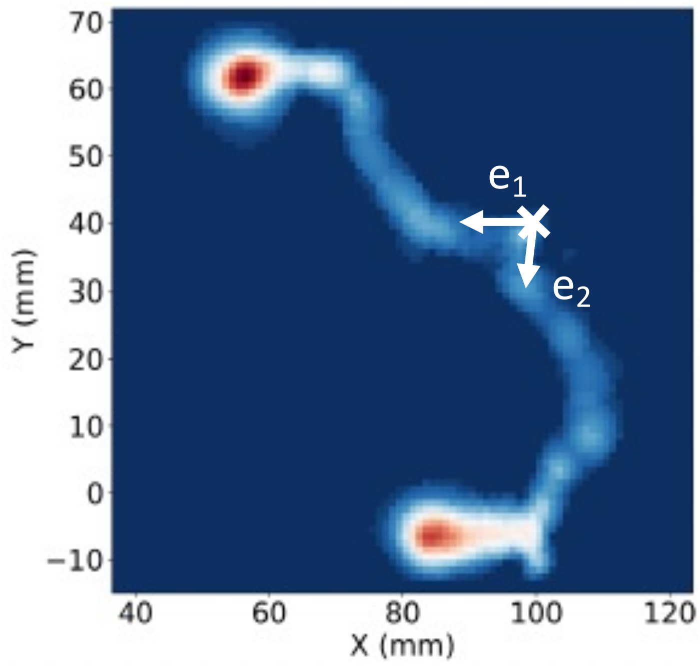
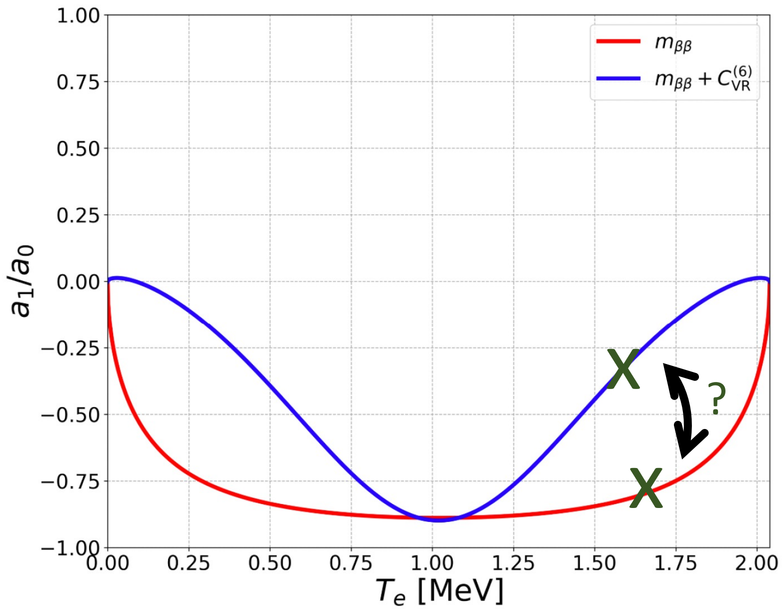


Figure made with νDoBE → generator to calculate your EFT event spectra!



I work on this, so it gets a slide :-)

Scholer, O., de Vries, J. & Gráf, L. *J. High Energ. Phys.* **2023**, 43 (2023).

Summary

- $0\nu\beta\beta$ is the most sensitive way to to probe the Majorana nature of the neutrino
- Majorana neutrinos provide a more natural way to explain the lightness of the neutrino mass, and are a prediction of theories such as leptogenesis
- Significant new theory efforts in the estimation of nuclear matrix elements with uncertainties, including recent ab-initio efforts
- Rich source of lepton number violating physics that could drive $0\nu\beta\beta$ beyond light-Majorana exchange